3S^2: Behavioral Response Studies of Cetaceans to Navy Sonar Signals in Norwegian Waters

Patrick Miller
Sea Mammal Research Unit, Scottish Oceans Institute
School of Biology, University of Saint Andrews
St. Andrews Fife, KY16 8LB UK
phone: (+44) 1334-463554 fax: (+44) 1334-463443 email: pm29@st-and.ac.uk

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http://www.smru.st-and.ac.uk

Peter Tyack
Senior Scientist Emeritus
Biology Department
Woods Hole Oceanographic Institution
266 Woods Hole Road, MS#50
Woods Hole, MA 02543, USA
phone: (508) 289-2818 fax: (508) 457-2041 email: ptyack@whoi.edu

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LONG-TERM GOALS

A primary goal of this international cooperative research program is to investigate behavioral reactions of three species of whales: bottlenose whales, minke whales, and humpback whales elicited by exposures to quantified dosages of naval active sonar signals in the 1-10 kHz range. The results are interpreted to generate dose-response functions, in order to help establish safety limits for sonar operations for these species. Another primary goal of the program is to assess the effectiveness of "ramp-up," a common mitigation protocol in which source levels are gradually increased prior to the onset of full-level transmissions. Ramp-up is designed to give nearby animals some time to move away before sonar transmissions reach maximum levels. However, it is unknown whether or not this protocol is actually effective for animals in their natural environment. We have developed and implemented an experimental design to test whether the 'ramp-up' procedure is an effective protocol to reduce risk of harm from sonar activities.

OBJECTIVES

In this research project, our specific objectives are to: 1.) Expand the 3S comparative dataset of behavioral response experiments to include species that are potentially more sensitive and difficult to study: Northern bottlenose whale (*Hyperoodon ampullatus*, family Ziphiidae) and minke whale (*Balaenoptera acutorostrata*, family Balaenopteridae). The goal is to identify behavioral response thresholds during experimental exposures, and to compare these to responses to no-sonar negative controls and positive controls consisting of playback of killer whale sounds; 2.) Study the

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effectiveness of ramp-up as a mitigation method with abundant and relatively easy-to-study humpback whales (*Megaptera novaeangliae*, family Balaenopteridae); 3.) Record sufficient no-sonar baseline data from all target species to adequately describe the behavioral significance of recorded changes in behavior and to statistically compare experimental records with baseline records; and 4.) Develop collaborations between the 3S research group with the MOCHA project and other research groups undertaking similar projects to pool data where appropriate, share expertise and reduce overall project costs.

APPROACH

Two of the species of whale selected for this study (minke and northern bottlenose whales) are North Atlantic species for which there is evidence of risk from sonar exposure. Sonar-related strandings have commonly involved Ziphiids in temperate or tropical waters, but in the North Atlantic have also included the Northern bottlenose whale (Canary Islands), and the minke whale (Bahamas). It is unclear whether the low numbers of Northern bottlenose whales and minke whales documented in sonar-related stranding events result from lower sensitivity to sonar or because they are present in lower numbers in the areas where stranding events have been documented. Directed research on the behavioral responses of these two species is needed to resolve this question (Tyack et al., 2004). The earlier 3S research effort (see related programs) with killer, sperm, and long-finned pilot whales provides a dataset that enables comparative analysis of behavioral response sensitivities. The $3S^2$ field experiments follow the same protocol of escalating the level received by the whale subject in order to identify the lowest threshold at which the subject responds. Playback of killer whale sounds is conducted as a positive control to assess how responses to sonar might be shaped by reactions to naturally aversive stimuli (Curé et al., 2012).

Similar experiments are needed to address the question of whether or not ramp-up is an effective mitigation measure. Animals close to the location of the first full-level sonar transmission are at the greatest risk of severe effects such as strong behavioral responses or hearing effects such as temporary or permanent threshold shift (left panel of Fig. 1). The ramp-up protocol could be effective if it gives animals time to move away from the immediate location of the full-level sonar pings (right panel of Fig. 1). Thus, the ramp-up protocol is itself is based upon the principle of behavioral response – in this case an avoidance response that protects the animals from receiving intense sound levels.

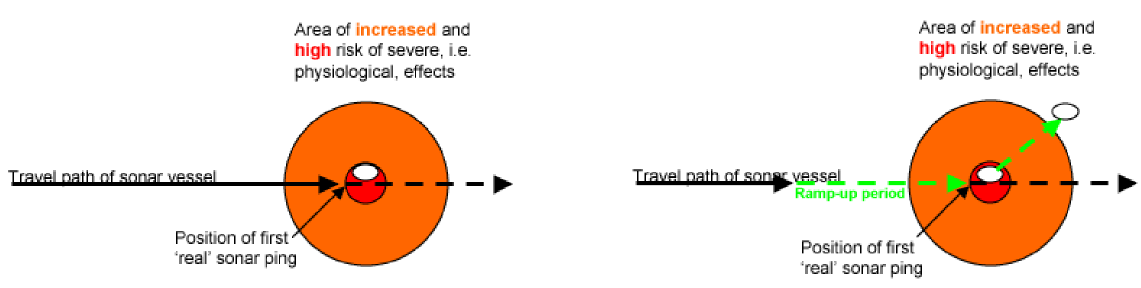


Figure 1. A conceptual diagram of the role of ramp-up before full-level sonar operations. Left: Animals near the position of the first full-power sonar transmissions are at a higher risk of severe effects. Right: The ramp-up procedure implies that sonar sounds are started earlier, at lower levels, and are gradually increased to full power at the planned position. These additional ramp-up transmissions are designed to give animals within the zone of increased risk time to move away.

Specifically, it is assumed that animals will move away from the source of sounds during ramp-up, even if the sounds are transmitted at relatively low source levels. Avoidance has been observed in several studies of marine mammals in the presence of noise (Richardson et al., 1995), but does not necessarily always occur (Miller et al., 2009). It is even possible that starting the sonar sounds at low levels will cause the animals to acclimate to the sound, thereby reducing any tendency to avoid the source. Second, it is assumed that animals will be able to sense the direction and path of the oncoming sound source and formulate a good direction to move away from the sound source. Moreover, it may take some time for animals to determine the direction and speed of movement of the vessel to make appropriate avoidance movements.

To study the effectiveness of ramp-up as a mitigation tool, we have quantified the likelihood of avoidance as a consequence of exposure to the ramp-up signals. This requires understanding what factors affect the probability of avoidance (e.g. received level at the animal, distance of the source, frequency or amplitude of the sonar, sound propagation conditions, behavioral state of the animal). As in behavioral response studies generally, we seek to understand what the consequences for the animals are, but in the case of ramp-up we specifically would like to know whether or not avoidance behavior leads to effective protection from high sound exposure levels.

The research is carried out by an international collaborative team from the Sea Mammal Research Unit (SMRU), Woods Hole Oceanographic Institution (WHOI), Norwegian Defense Research Establishment (FFI), and Netherlands Organization for Applied Scientific Research (TNO). WHOI provides v2 Dtags, and development in collaboration with Lars Kleivane of a pneumatic launching system for the Dtag, and tagging support for the field work. Project management and logistic support, including acquisition of research vessels and permitting are managed through FFI, led by Dr. Petter Kvadsheim. FFI also provides biological and tagging expertise, including the development of a new pneumatic launching system for the Dtag, with the FFI part of the effort headed by Lars Kleivane. TNO contributes an advanced towed array system for recording and detecting marine mammal sounds (Delphinus), a multi-purpose towed source (Socrates), and staffing during the cruises under the leadership of Frans-Peter Lam, with collaboration from René Dekeling of the Royal Netherlands Navy. The Socrates source is capable of transmitting 1-2 kHz signals at a source level of 214dB re1µPa m. Miller of SMRU at the University of St Andrews leads the analysis team and Tyack also from SMRU is a member of the 3S^2 board, provides scientific advice, oversees postdoctoral research, and acts as liaison with the WHOI tagging team.

WORK COMPLETED

All dedicated fieldwork for the 3S^2 project was completed in 2013 (Kvadsheim et al., 2013). 3S^2 collaborated with a 2014 field project funded the US Strategic Environmental Research and Development Program (SERDP) to collect additional baseline data on the northern bottlenose whales. The 3S^2 data includes a total of 11 humpback whales tagged with Dtag version 2 plus Sirtrac GPS loggers. These humpback whales were subject to 11 no-sonar control sessions, 20 1-2 kHz upsweep exposure sessions, and 8 killer whale sound playbacks with separate noise control playbacks. One minke whale was tagged in 2011 using a dive logger tag, during which one no-sonar control and one 1-2kHz upsweep sonar exposure session was conducted. For the northern bottlenose whale, we conducted one experiment in 2013 with a whale tagged with a Dtag version 2, during which one 1-2 kHz upsweep sonar exposure was conducted. Five additional baseline records were obtained for the northern bottlenose whale in summer 2014 via the collaborative research with the SERDP-funded project.

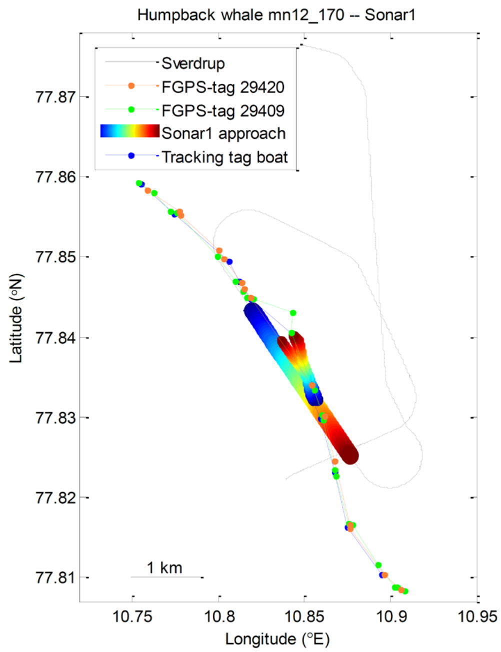
In this fiscal year, we focused our efforts on data analysis and derivation of core results for the project. As we conducted for 3S species (killer, long-finned pilot, and sperm whales) under the first increment of this award (Miller et al., 2012), we have prepared a set of standardized plots detailing the horizontal and time-series behavioural data of each subject whale from our 3S experiments. As is clearly apparent in an example plot (Fig. 1), our field observations provide a broad suite of data streams that are useful to reconstruct details of the behavior of each subject animal before, during, and after each exposure or control session.

Using these standardized plots for all experimental and control exposure sessions, the 3S collaborative team held focused expert-scoring sessions in which we carefully evaluated the outcome of each experiment, following the severity scale first introduced by Southall et al. (2007) and later applied to 3S experiments (Miller et al., 2012). This expert evaluation is now complete and the results are being prepared for publication.

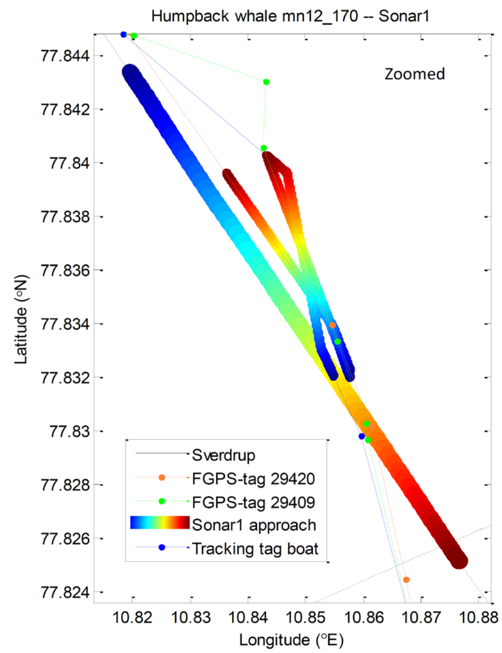
In addition to expert-scored evaluation of the outcome of all of the $3S^2$ experiments using the Southall et al. (2007) severity scale, we have also made substantial progress over this fiscal year on quantitative evaluation of the effects of sonar and killer whale playbacks on the movement and foraging behaviour of humpback whales and the effects of sonar on the northern bottlenose whale. Finally, we have developed a complete framework to evaluate the effectiveness of ramp-up based upon our experiments with humpback whales, which will be finalized by the end of the current award.

Results of the 3S research efforts under this program have been presented at the 2013 Biennial meeting of the Society for Mairine Mammalogy in Dunedin, New Zealand, and at the 2014 Bio-logging symposium in Strasbourg, France. Several additional papers have progressed toward publication in theses and peer review journals (see Publication list).

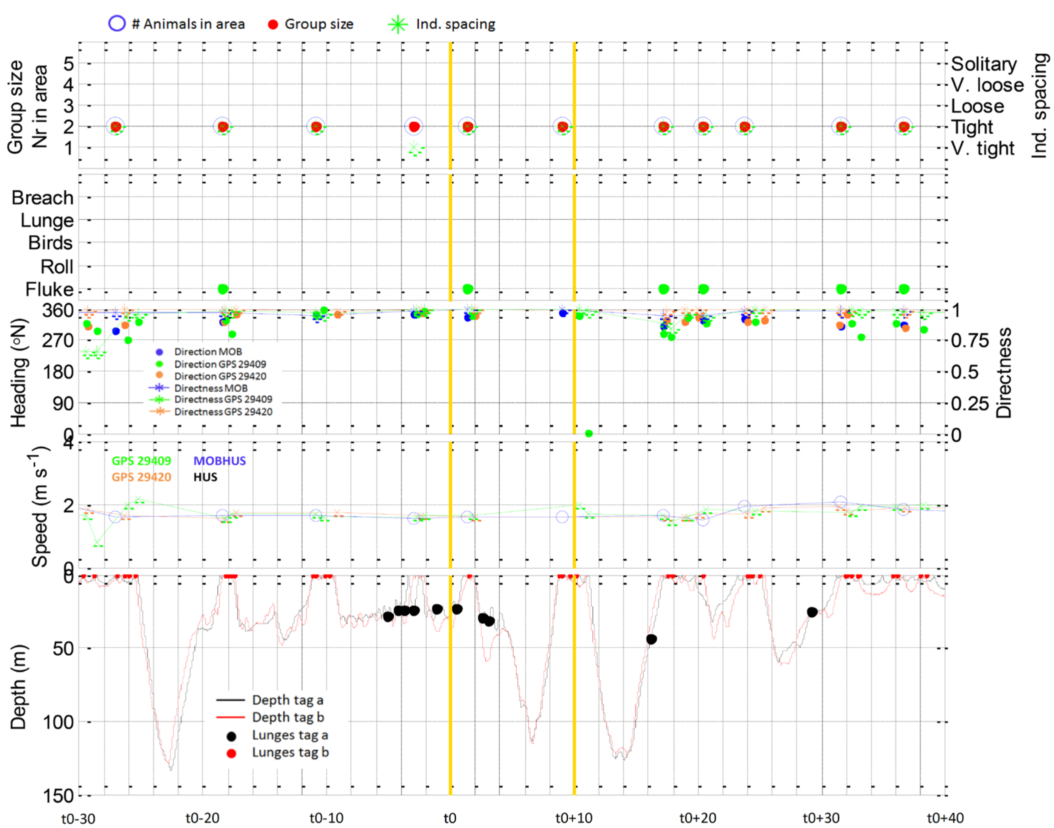
SONAR 1



Humpback whale mn12_170 -- Sonar1
Sverdrup
FGPS-tag 29420
FGPS-tag 29409
Sonar1 approach
Tracking tag boat
1 km
Latitude (°N)
77.87
77.86
77.85
77.84
77.83
77.82
77.81
10.75
10.8
10.85
10.9
10.95
Longitude (°E)



Humpback whale mn12_170 -- Sonar1
Zoomed
Sverdrup
FGPS-tag 29420
FGPS-tag 29409
Sonar1 approach
Tracking tag boat
Latitude (°N)
77.844
77.842
77.84
77.838
77.836
77.834
77.832
77.83
77.828
77.826
77.824
10.82
10.83
10.84
10.85
10.86
10.87
10.88
Longitude (°E)



Animals in area
Group size
Ind. spacing
Group size
Nr in area
Solitary
V. loose
Loose
Tight
V. tight
Ind. spacing
Breach
Lunge
Birds
Roll
Fluke
Heading (°N)
Direction MOB
Direction GPS 29409
Direction GPS 29420
Directness MOB
Directness GPS 29409
Directness GPS 29420
Directness
GPS 29409
GPS 29420
MOBHUS
HUS
Speed (m s-1)
Depth (m)
Depth tag a
Depth tag b
Lunges tag a
Lunges tag b
t0-30
t0-20
t0-10
t0
t0+10
t0+20
t0+30
t0+40

Figure 1. Plot showing detailed data recorded during the first sonar exposure session conducted with humpback whale subject mn12_164. Note that two associated whales were tagged, but only one focal whale in the group of two was tracked with visual observations. The top two panels show the horizontal movements of the whale based on the visual observations (blue) and the GPS (green) in relation to the approaching source vessel (Sverdrup). The colorbar on the whale and source tracks indicate the phase of the exposure, with blue and red indicating the start and end of the exposure session, respectively. The lower panels plot time-series of various data timeseries, with yellow lines indicating the start and stop of the sonar exposure. Panels from the top show: 1) Group structure variables; group size, number of animals in the area and group spacing (distance between animals in focal group, measured in body lengths); 2) Different social variables; observed breaches, surface lunges, rolls, flukes and if there were birds surrounding the focal animal(s); 3) Heading and directness (a measure of how straight the animal is swimming, 1=straight line, 0=circular), measured from the visual observations and GPS; 4) Speed of the animal, measured from visual observations (blue) and GPS (green); and 5) Dive profile (black) with detected lunges marked as red dots in the bottom panel.

RESULTS

Expert scoring of responses during 3S experiments and their severity:
The 3S collaborative team followed a structured protocol to carefully examine the data from each experiment (see example Fig. 1), and to determine whether or not a behavioral response was judged to have occurred and what to score the severity for each response. Two independent groups met separately, and then a final consensus opinion was obtained by the two groups reconciling their independent scores with the aid of a third-party adjudicator.

For the example provided here (Fig. 1), the final consensus was that no responses to the sonar exposure were observed in terms of horizontal movement or social behavior. Some variations in the dive profile were not considered likely to be a response to the sonar as similar levels of variation were observed in the baseline record for the whale. The panel did agree that there was a clear indication of cessation of feeding by the whale, which was conducting lunges just prior to the start of the sonar transmission (black dots in bottom panel of Fig. 1). Some lunges were observed later after the sonar stopped transmitting, so the duration of the scored response was considered to be 'moderate', which led to a severity score of 6 following the definitions in the Southall et al. (2007) and Miller et al. (2012) severity tables. That definition relates the severity of a behavioral change to the duration of the behavioural response in relation to the duration of the exposure. Responses that end during an exposure are considered less severe than responses that last roughly as long as the exposure ('moderate' responses) or those that last considerably longer than the exposure ('prolonged' responses).

One of the key goals of expert scoring of all experiments is to contrast the severity of scored responses across the different exposure types (controls vs sonar exposures). As we had found previously for the 3S species (killer, long-finned pilot, and sperm whales), the responses for which the highest severity was scored occurred during exposure sessions with actual sonar transmissions (Sonar 1 and Sonar 2 in Table 1), or during playback of killer whale sounds ('KWPB' in Table 1). The maximum severity was particularly high during KWPB sessions, with 7/8 sessions having a maximum severity response scored 4 or greater. Maximum severity responses during sonar sessions were also high, but responses were more severe during the first sonar exposure than a second sonar exposure. Second sonar

exposures were only conducted for humpback whales. This result indicates that humpback whales appear to habituate to the sonar exposure following the first exposure session.

Some responses were scored during no-sonar control sessions, but these were of lower severity than sonar or killer whale playback sessions. During no-sonar controls, the source vessel operated precisely as it would during an actual sonar exposure session, but no signals were transmitted from the source. No response at all was scored for 8/13 no-sonar controls, and only one session contained a scored response judged to be greater than severity 3 on the Southall et al. (2007) scale. This result is important as it strongly indicates that while whales may respond to the vessel itself, the high-severity scored responses of the whales during sonar sessions were not likely to have been due to the vessel approach itself.

Table 1. Maximum severity of scored responses during each exposure session by stimulus type for all 3S^2 experiments. Data are pooled across the three species and are grouped by exposure type. The summary shows total number of sessions for each exposure type, and the percentage of scoring session that had maximum severity ≥ 4.

Severity	*no-sonar control*	*Sonar1*	*Sonar2*	*KWPB*	*control-PB*
9					
8		2			
7		1		3	
6		3	2	3	1
5		2	1	1	1
4	1	2	1		1
3	3		2		
2	1	2	1	1	
1					
0	8	1	3	0	5
Total # of sessions	13	13	10	8	8
% severity 4 to 9	7.7	76.9	40.0	87.5	37.5

Northern bottlenose whale experiment:

In 2013, we conducted one sonar exposure to a northern bottlenose whale off Jan Mayen Island. We have now concluded detailed quantitative analyses of the subject whale during and after the sonar exposure (Fig. 2), and related the diving behavior of this whale to baseline behavior of eight tag records of bottlenose whales tagged in the Gully off Eastern Canada, and five records of bottlenose whales tagged off Jan Mayen in June, 2014. Substantial changes in dive behaviour and movement direction occurred close to the beginning of the deep dive as the received levels of sonar were escalating from roughly 100-125 dB re 1µPa rms (Fig. 2, inset box). The whale appears to have switched from what started as a shallower dive into an unusual silent deep dive, similar to responses described for other beaked whales exposed to sonar (Tyack et al. 2011; DeRuiter et al., 2013). Inspection of baseline tag records indicates that dives of whales greater than 500m depth consistently relate to foraging as indicated by the production of foraging clicks and buzzes by the tagged whale (Fig. 1). The silent deep dive performed by this whale is highly unusual both for being the longest-duration and deepest dive recorded for the species, and the fact that no foraging-related sounds were produced during the dive.

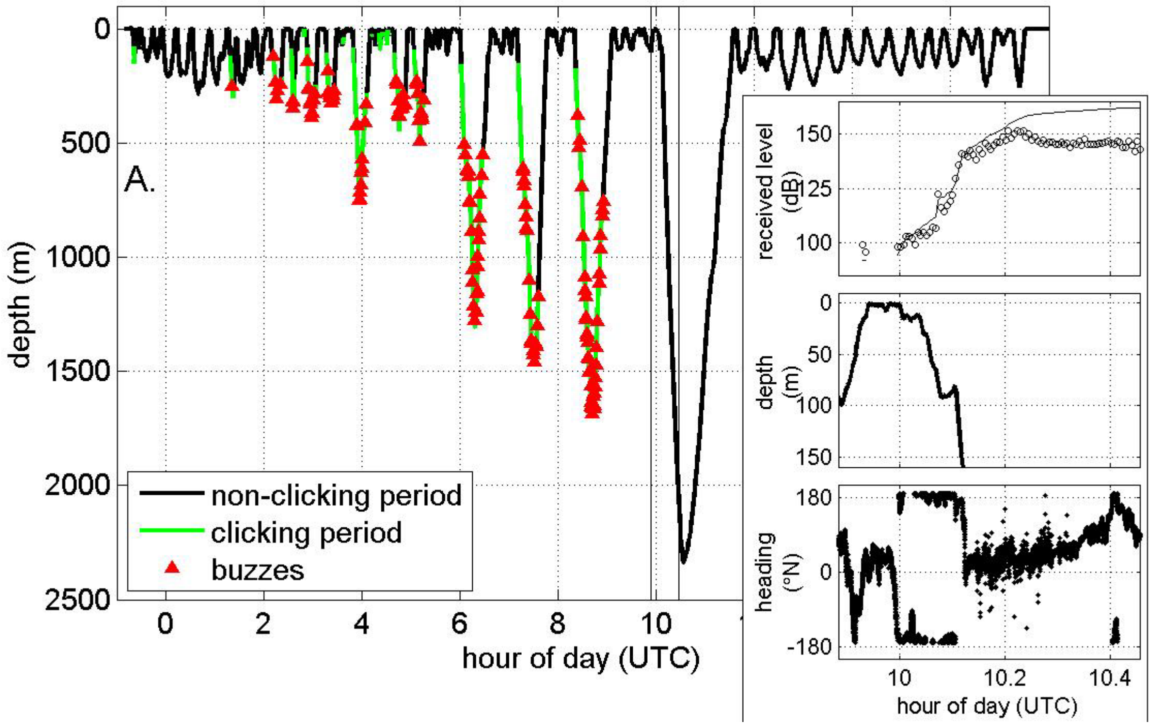


Figure 2. Time-depth record of tagged whale ha13_176a with the timing of the sonar exposure period marked with vertical lines bracketing 10 hour UTC. Sounds produced by the whale are marked by colour on the dive profile: black indicates periods when no foraging sounds were produced by the tagged whale, green shows periods when the tagged whale was producing foraging echolocation clicks, and red triangles indicate buzzes (i.e., likely foraging attempts). The inset box shows received levels of the sonar with sound pressure level shown as 'o' and cumulative sound exposure level as a solid line (top), depth (middle) and whale heading (bottom) during the exposure period.

RELATED PROJECTS

This study is a second phase of the project "Cetaceans and naval sonar: behavioral response as a function of sonar frequency" award number N00014-08-1-0984, which expired in 2011. A third phase of research focusing on the biological relevance of behavior associated with 3S experiments has begun this year under award number N00014-14-1-0390. Statistical support and collaboration is ongoing with the MOCHA project award N00014-12-1-0204. Collaborative research is pursued with Kelp Marine PI Fleur Visser under award N00014-11-1-0298.

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